FEASIBILITY STUDY OF HEAVY ION STORAGE AND ACCELERATION IN THE HESR WITH STOCHASTIC COOLING AND INTERNAL TARGETS

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Abstract

The option of heavy ion stochastic momentum cooling is investigated under the constraint of the present concept of the High Energy Storage Ring (HESR). A bare uranium beam is injected from the collector ring (CR) into the HESR at 740 MeV/u and a beam preparation for an internal target experiment is outlined. Further the acceleration of the ion beam to 2 GeV/u is considered and an internal target experiment is studied. The simulations include the beam-target interaction due to a Hydrogen target. The capability of momentum Filter cooling is envisaged and at lower energies where the revolution harmonics begin to overlap the possibility of Time-Of-Flight (TOF) momentum cooling is examined. The simulation studies make use of a Fokker-Planck and a two-dimensional tracking code in longitudinal phase space to predict the ion beam properties for an internal target experiment.

INTRODUCTION

In the present investigation the feasibility of the HESR storage ring [1] for the application of heavy ion beams in internal target experiments with stochastic momentum cooling is investigated. The study complementing the previous results [2] is carried out under the constraint of the available cavity voltages in the HESR to capture and accelerate an ion beam. In addition to a Fokker-Planck equation (FPE) description [2] a two dimensional particle tracking code in longitudinal phase space taking account also for the ion's synchrotron motion due to the RF fields is therefore applied. The injection and the longitudinal cooling process assisted by a barrier bucket (BB) cavity to compensate the strong mean energy loss of the ion beam due to an internal target is examined.

A bare $^{238}U^{92+}$ beam is kicked injected from the collector ring (CR) into the HESR with longitudinal beam properties that have been recently studied in detail in [3]. All calculations include intra beam scattering (IBS) as outlined in [2]. It is assumed that transverse cooling is applied to compensate the emittance increase due to the beam-target interaction. The horizontal as well as vertical emitttance is $\varepsilon_{rms} = 0.125$ *mm mrad*. Adiabatic phase space damping with a dilution of 25 % is applied when the ion beam is accelerated to higher energies. The lattice with zero dispersion in the straights has been optimized for internal target experiments and stochastic antiproton cooling with $\gamma_{tr} = 6.23$. A hydrogen target with density $N_T = 4 \cdot 10^{15}\ cm^{-2}$ is used [2].

The application of the new 2 MeV electron cooling system, presently mounted at COSY, to heavy ion cooling has been complementary studied in a detailed separate contribution [4].

COOLING AT 740 MeV/u

To transfer the beam from CR to the HESR it is essential to provide a gap of 200 ns for the CR's extraction kicker. Therefore, an adiabatic capture of the DC-beam with N = 10^8 ions is carried out [3]. The initial rms-relative momentum spread, $1.5 \cdot 10^{-4}$, of the DC-beam will increase to $\sigma_p = 3.3 \cdot 10^{-4}$ (rms) while the beam becomes bunched with an rms-bunch length of 110 ns. A nearly Gaussian shaped ion beam is then kicked-injected into the HESR. Two possibilities exist to further process the incoming bunch. For an internal target experiment at 740 MeV/u the beam could be injected into the barrier bucket and after de-bunching to a nearly DC-beam could be cooled stochastically. However the momentum spread of the incoming beam with $3\sigma_p = 9.9 \cdot 10^{-4}$ significantly exceeds the bucket height, $(\Delta p/p)_{bucket} = \pm 4 \cdot 10^{-4}$, for the available BB cavity operating at a frequency $f_{BB} = 5\ MHz$ with a peak voltage 2 kV. To circumvent the beam is injected into the bucket of the h = 1 cavity which features a large enough bucket height of $(\Delta p/p)_{bucket} = \pm 1.2 \cdot 10^{-3}$ at a peak voltage of 2 kV. The cavity voltage is then exponentially reduced to 100 V within 500 ms thereby adiabatically diminishing the relative momentum spread in the ion beam to $\delta_{rms} = 1 \cdot 10^{-4}$. The rms-bunch length increases to $\approx 360\ ns$. At the end of the capture procedure the beam well fits into the cooling acceptance $\Delta p/p = \pm 7 \cdot 10^{-4}$ for the Time-Of-Flight (TOF) cooling method which will be applied at the lower beam energies in the HESR as outlined in [2]. Furthermore the relative momentum spread of the beam is now small enough to be captured by the BB cavity with 2 kV peak voltage. After 500 ms the h = 1 cavity is switched OFF and the barrier bucket cavity is turned ON. The beam will de-bunch in 50 ms and becomes a quasi DC beam with a 10 % gap. It is now ready for TOF cooling and the internal target experiment at 740 MeV/u.

Stochastic Momentum Cooling with Internal Target at 740 MeV/u

Tracking simulation results of TOF momentum cooling applying the HESR (2 – 4) GHz cooling system [5] with 85 dB electronic gain at 740 MeV/u are shown in Figure 1. The figure depicts the time evolution of the relative momentum spread and compares the tracking results with

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a FPE prediction. At time t = 0 s the h = 1 cavity is switched OFF and the BB cavity is switched ON. The cooling system and the internal target are switched ON at t = 1 s. The figure shows a fairly well agreement between the predictions from FPE (red) and tracking (blue) for the first 1.5 s. The initial increase of the momentum spread for the first 1 s is due to IBS. For t > 1.5 s both predictions diverge which can be ascribed to the fact that the one-dimensional FPE code does not include the barrier cavity. Instead, to first order, it is assumed that the mean energy loss can be compensated by the BB. The larger rms-values result from the synchrotron motion of the ions in phase space subject to the mean energy loss in the target and the cooling force as well as the strong heating by Schottky particle noise in the case of TOF cooling [2], leading especially to the 38 % larger equilibrium value $\delta_{rms}^{eq} = 5.5 \cdot 10^{-5}$ as shown.

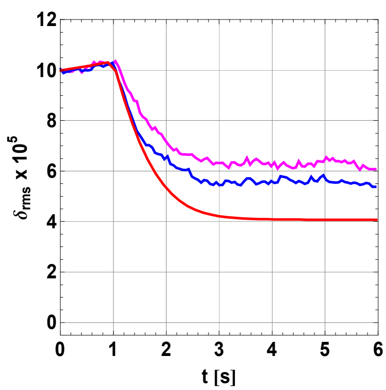

Figure 1: Time evolution of the rms-relative momentum spread during cooling and internal target operation at 740 MeV/u. The red curve shows the FPE prediction while the tracking results are given by the blue and violet curves.

The initial (t = 0 s) and final (t = 6 s) phase space is shown in Figure 2. It is clearly visible that the tracking simulations confirm that the strong mean energy loss is compensated by TOF cooling assisted by the BB cavity.

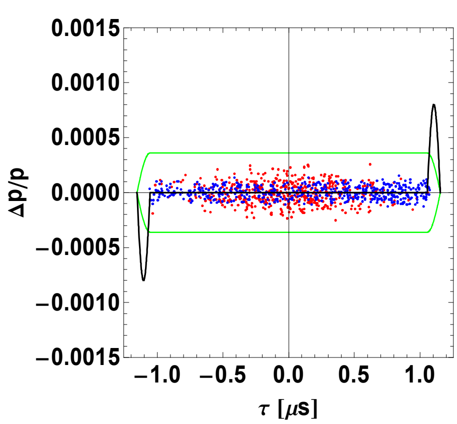

Figure 2: Phase space portrait at t = 0 s (red) and t = 6 s (blue). The separatrix of the BB cavity is drawn in green. The BB voltage is shown in black. The mean energy loss is compensated and the beam is a quasi DC beam.

After 4 s of the cooling the beam is a quasi DC beam with a 10 % gap produced by the BB cavity and 60 % of all ions are confined in $-5 \cdot 10^{-5} \le \Delta p/p \le 5 \cdot 10^{-5}$. No beam loss occurs.

In addition a tracking simulation has been carried out for the case that the electronic delay in the cooling system is not set to the flight time from pickup to kicker of a nominal particle. Instead, a delay error of 37 ps is assumed. This corresponds to a phase error of 40 degree in the center of the cooling bandwidth. Figure 1 shows that in this case the equilibrium value increases only by 10% to $\delta_{rms}^{eq} \approx 6 \cdot 10^{-5}$. The mean energy loss is still compensated. No beam loss occurs. From the simulation it is concluded that a 10 degree phase stability as is envisaged for the cooling system [5] is tolerable.

INJECTION AND ACCELERATION

Since the maximum magnetic field ramp rate in the HESR is limited to $dB/dt = 25\ mT/s$ and the maximum h = 1 cavity peak voltage to 2 kV the maximum achievable energy gain per nucleon per turn of an bare uranium ion is $dT = 0.165\ keV/u/turn$. As an example the acceleration to 2 GeV/u is considered here which is carried out within 17 s. A magnetic field ramp consisting of a quadratic transition (200 ms) to the linear ramp with constant energy gain and a quadratic transition (200 ms) to flat top is used for beam acceleration. The ion beam from the CR is kicked-injected into the standing bucket of the h = 1 cavity with 2 kV. Tracking simulations have been then carried out to simulate the injection process and the acceleration to 2 GeV/u. The simulation includes an adiabatic reduction of the momentum spread within 500 ms when the beam has reached flattop energy. Applying this procedure leads to a nearly Gaussian shaped ion bunch with $\delta_{rms} = 1 \cdot 10^{-4}$ and an rms-bunch length $\sigma_\tau = 190\ ns$. The momentum spread is now small enough so that fast Filter momentum cooling with its smaller cooling acceptance [2] can be applied.

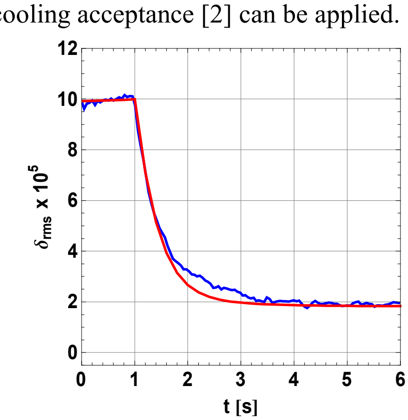

Figure 3: Time evolution of the rms-relative momentum spread during cooling and internal target operation at 2 GeV/u. The red curve shows the FPE prediction while the tracking results are given by the blue curve.

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The time evolution of the momentum spread and the particle momentum distributions as predicted by tracking and FPE is shown in Figure 3, respectively in Figure 4. At time t = 0 s the h = 1 cavity is switched OFF and the BB cavity is switched ON. The beam will de-bunch in 100 ms and becomes a quasi DC beam with a 10 % gap. The Filter cooling system with 108 dB gain and the internal target are switched ON at t = 1 s. The beam is cooled down to an equilibrium value $\delta_{rms} = 2 \cdot 10^{-5}$ within 4 s. A remarkable agreement between FPE prediction, neglecting the mean energy loss, and the tracking results, including the mean energy loss, is found.

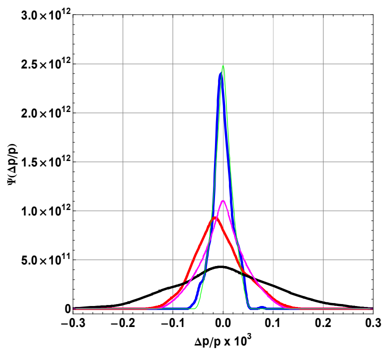

Figure 4: Momentum distributions during cooling. Black: The initial distribution, Comparison of FPE predictions (violet, t = 1.5 s; green t = 6 s) with a tracking results (red, t = 1.5 s; blue, t = 6 s).

This result can be assigned to the now stronger cooling force of Filter cooling and, due to the Filter application, the reduced particle Schottky and thermal noise contribution to the unwanted heating of the beam. Moreover, at this energy the ring's frequency slip factor is only $\eta = 0.075$ as compared to $\eta = 0.28$ at 740 MeV/u.

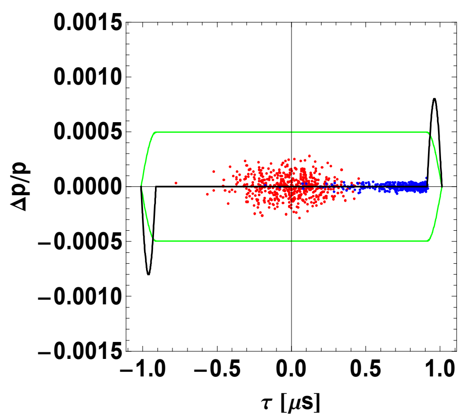

Figure 5: Phase space portrait at t = 0 s (red points) and t = 6 s (blue points). The separatrix of the BB cavity is drawn in green. The BB voltage is shown in black. The mean energy loss is compensated. The beam is now strongly bunched after 6 s (blue points).

The drift motion between the barriers becomes slower, especially for ions with lower momentum spreads which finally results now in a bunched beam with a bunch length of about 400 ns, blue points in Figure 5. Comparing these results with a simulation in which the target is turned OFF during cooling, Figure 6, shows that the only effect of the target is that the beam becomes bunched. The final momentum spread found from Figure 6 is nearly the same as that observed in Figure 3.

Table 1 summarizes the equilibrium values and cooling down times for both energies.

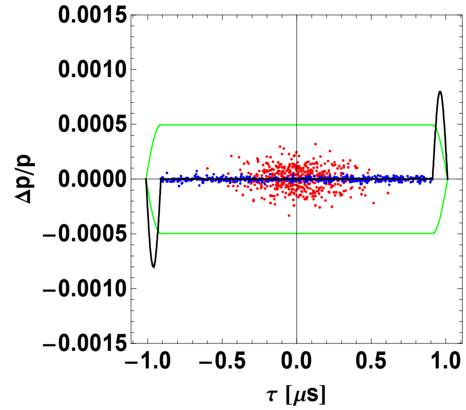

Figure 6: As in Figure 5, but the target is switched OFF.

Table 1: Beam Equilibrium and Cooling Down Time

T [MeV/u]	$\Delta p/p_{rms,\ equilibrium}$	Bunch length	cooling down time t_{EQ} [s]	cooling method
740	$5.5 \cdot 10^{-5}$	Quasi DC	4	TOF
2000	$2 \cdot 10^{-5}$	≈ 400 ns	4	Filter

CONCLUSION

The present investigation reveals that the available cavity voltages in the HESR are sufficient for capture, preparation and acceleration of a bare uranium ion beam bunch in the HESR. The beam can either be prepared with TOF stochastic cooling for an internal target experiment at 740 MeV/u or it can be accelerated to 2 GeV/u within 17 s with the maximum available magnetic ramp rate. Fast stochastic Filter momentum cooling can then be applied assisted by the BB cavity. The tracking simulations predict however a strong bunching at 2 GeV/u during target operation. This effect will be studied soon in detail experimentally at COSY where stochastic cooling, either with the TOF or Filter technique, BB operation and internal targets are well established [6].

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